Structural Health Monitoring of Repairs

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ABSTRACT

The process of implementing a damage identification strategy for aerospace, civil and mechanical engineering infrastructure is referred to as structural health monitoring (SHM). This process involves the observation of a structure or mechanical system over time using periodically spaced measurements, the extraction of damage-sensitive features from these measurements and the statistical analysis of these features to determine the current state of structural health. For long-term SHM, the output of this process is periodically updated information regarding the ability of the structure to continue to perform its intended function in light of the inevitable aging and damage accumulation resulting from the operational environments. Under an extreme event, such as an unanticipated blast loading, SHM could be used for rapid condition screening. This screening is intended to provide, in near real-time, reliable information about system performance during such extreme events and the subsequent integrity of the structure. [1]

This paper describes the scope of SHM, its general requirements and architecture, and it provides an insight on damage monitoring of repairs. Benefits and obstacles of structural health monitoring of repairs are discussed.

1.0 INTRODUCTION

The process of implementing a damage identification strategy for aerospace, civil and mechanical engineering infrastructure is referred to as structural health monitoring (SHM). Here, damage is defined as changes to the material and/or mechanical properties of a structure, including changes to the boundary conditions, which adversely affect the structural performance. A wide variety of highly effective local non-destructive evaluation tools are available for such monitoring. However, the majority of SHM research conducted over the last 30 years has attempted to identify damage in structures on a more global basis. The past 10 years have seen a rapid increase in the amount of research related to SHM and its associated potential for significant life-safety and economic benefits has motivated the need for further development. [1]

In order to increase the mission availability, maintenance-induced downtime must be reduced. SHM offers the opportunity to reduce inspection efforts and optimize maintenance and mission planning. This is in particularly true for monitoring of repairs. SHM offers benefits in view of being able to continuously monitor the structural integrity of a repaired structure as described in the following sections.

2.0 STRUCTURAL HEALTH MONITORING

2.1 Definition

The aim of Structural Health Monitoring Systems is to monitor the structural condition of an aircraft or aircraft structure. To ensure the structural integrity of the airframe and structural systems by modern structural health monitoring systems the four main functions, shown in Figure 2.1-1 are essential: event

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14. ABSTRACT
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15. SUBJECT TERMS

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and fatigue life monitoring, including remaining life assessment with interface to logistic support and damage monitoring. [2]

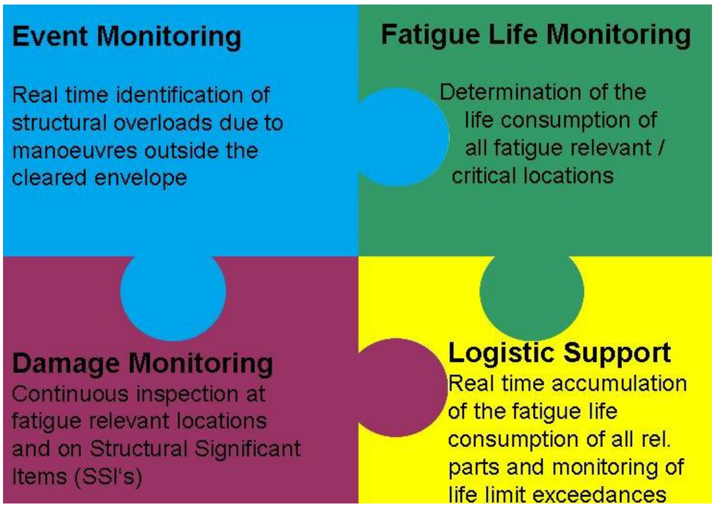

Figure: 2.1-1: Main parts of a modern SHM-System [2]

In detail, the first function, monitoring of selected structural events, includes real time monitoring of every structural load exceedances, resulting from a usage outside the cleared envelope (for military fighter aircraft mainly due to manoeuvres. This function is related to the requirements of airframe safety and certification.

The second function, fatigue life monitoring, includes the usage monitoring and the monitoring of the life consumption of all fatigue relevant and critical locations. The monitoring of the life consumption against the certified life of the structure is the main task here, in order to fulfil the airframe certification requirements.

The third function, damage monitoring, is the area of continuous and automated inspections at fatigue relevant locations and Structural Significant Items (SSI's) including all areas which are exposed to a high risk of impacts causing structural damage or an operational impact due to damage (e.g. impact damage on a radome structure). In addition, the monitoring of the long term damage propagation is a special task here, which requires sophisticated diagnostic and prognostic capabilities. This function is again related to the requirements of airframe safety and certification and to the requirements of mission assurance.

The fourth function, logistic support, is based on the capabilities of all three previous functions and uses its results to monitor life time and fatigue life exceedances in real time. It provides the essential life parameter, like remaining useful life, to the logistic and maintenance support system. Sophisticated prognostic capabilities for aircraft usage and damage assessment are required for this task. In addition to the requirements of airframe safety and certification, the main requirements for this function are related to mission assurance and operational philosophy, in connection to logistic concepts like condition based maintenance (CBM).

2.2 General Requirements of SHM Systems

A modern SHM system has to fulfil not less than four conditions, airworthiness, satisfactory defect detection capabilities, cost efficiency, and durability. The last condition establishes probably the hardest restriction. Producers and customers demand that a SHM system must have about the same lifetime such as an aircraft which is in the range of 30 years. This means that the sensor network should be more durable

than the structure under investigation. A related issue of SHM systems is to address all the environmental conditions that occur during operations. Outside the fuselage for example, changes in temperature range up to 200 K. These temperature changes strongly influence the accuracy of the SHM measurements. Finally, such as mentioned above, the data obtained from SHM systems must finally be integrated into a structural health management systems. [3]

The implementation of an SHM system has to be accompanied by all the certification procedures that are required if analogous aircraft systems are replaced or modified.

2.3 Elements of a Damage Monitoring System

The major elements of a damage monitoring system are shown in Figure 2.3-1. For a robust and efficient monitoring, the monitoring system consists of several design elements with defined interfaces.

The raw monitoring signals are generated by a sensor with is directly connected or integrated in the structure or repair. In Figure 2.3-1, the design element 1 is showing a surface mounted sensor. The sensor is connected by wires or wireless to the interrogation unit. The interrogation unit collects the raw data from several sensors. Depending on the technologies a first data manipulation and if needed data converting is performed here in order to provided the relevant monitoring data digital to an aircraft bus system. The monitoring data from the bus system are transferred to the next design element (element 4), where an onboard processing and data storage are performed. Modern system will have an integrated health management (HM) system with a central control and processing unit and data storage for all connected aircraft system. The onboard data are transferred to the ground element of the health management system. The main data processing activities and the detailed data analyses are performed in this design element (element 5) with sophisticated diagnostic and prognostic features. Finally, for data and analysis interpretation the results are provided to the engineering and maintenance staff. [2]

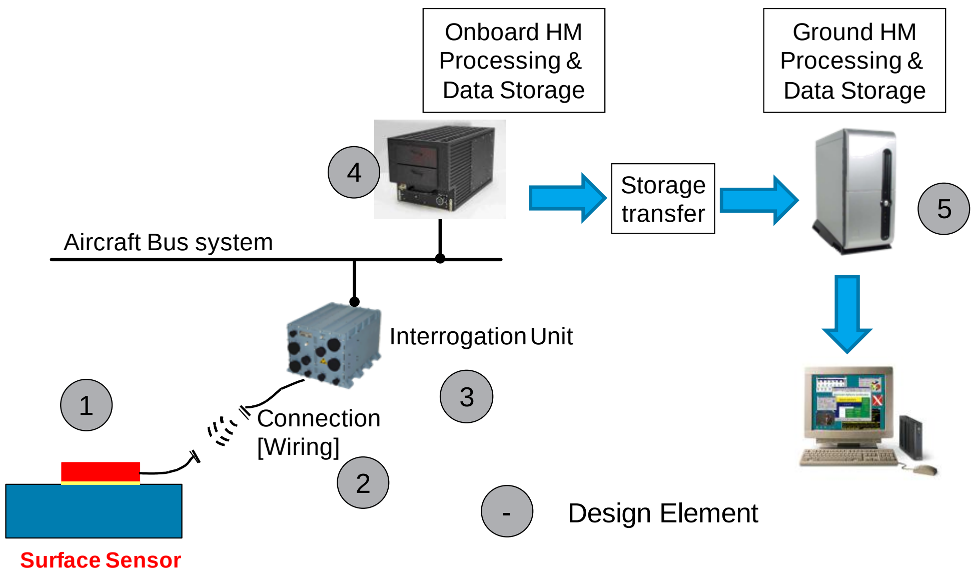

Figure 2.3-1: Generic overview of elements of a damage monitoring system

2.4 System Architecture

The proposed strategy for an SHM system is to integrate both usage and damage detection in order to emphasise that both aspects are necessary and they complement each other. For this approach a global system architecture is necessary which allows direct interfaces to other aircraft system.

The core of the proposed integrated health monitoring system is based on an Open System Architecture for Condition-based Maintenance (OSA-CBM)[4,5], as shown in Figure 2.4-1. Each sub-system contains the Data Acquisition (DA), Data Manipulation (DM) and State Detection (SD) layers locally, whilst the Health Assessment (HA), Prognostic Assessment (PA) and Advisory Generation (AG) layers are centralised within the health management core which correlates the health-related messages arriving from each sub-system. After landing, the PA interacts with the aircraft Configuration Management database and the Mission Planner in order to produce an appropriate AG for each aircraft. Then, the AG routine instructs the Command and Control, Mission and Maintenance crews on the combined diagnostic and prognostic assessment of the systems managed within the IVHM such that maintenance activities are planned with minimal interference to the mission schedule. Thus, the implementation of such Condition-based Architecture enhances the Mission Capability Rate by increasing the fleet availability. [6]

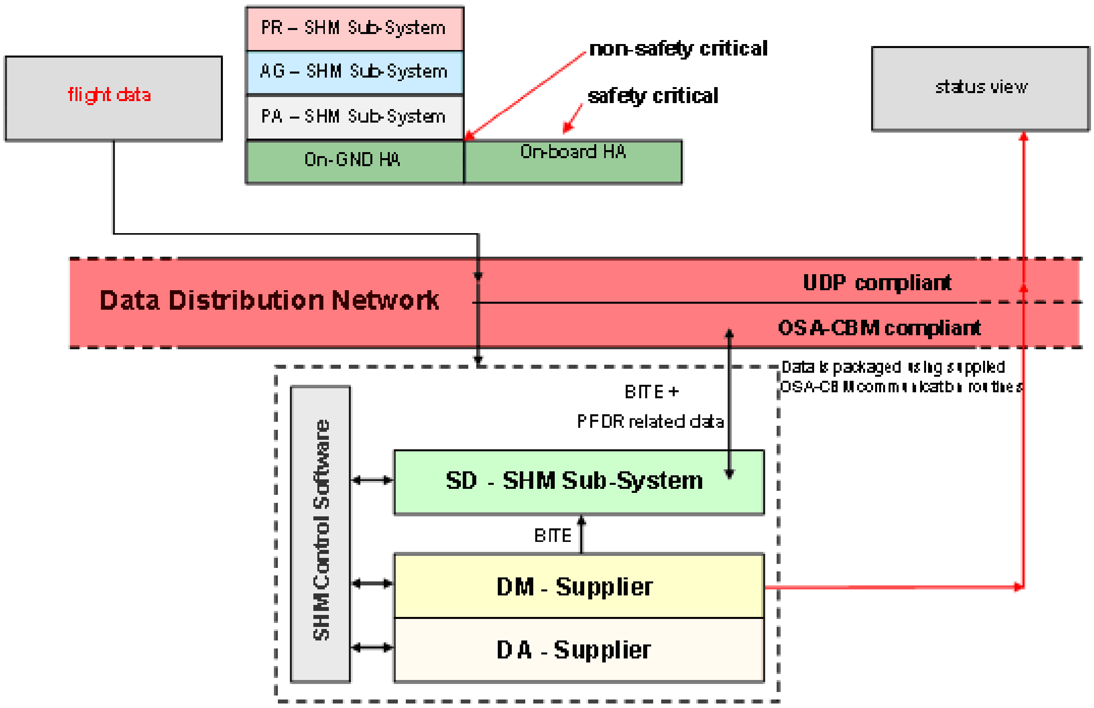

Figure 2.4-1: OSA – CBM System Architecture for SHM

2.5 State of the art of Damage Monitoring

The following table gives an overview on the main applied sensor technology with respect to the damage-related properties.

Technology/ Damage	Acoustic Emission	Acousto Ultrasonic	Phased Array Ultrasonic	Fibre Bragg Gratings	Comparative Vacuum Monitoring
Cracks	MMM CCC	MMM CCC	MMM C	MM CC	MMM CCC
Delamiantion	CCC	CC	C	CC	C
Impacts	MM CC			M C	
Corrosion		MM	MM		M

Table 2-1: Selected sensor technologies in relation to structural damage, C=composite, M=metal

Acoustic Emission

Acoustic Emission (AE) uses the effect of sound waves propagating through a material. A displacement of a material causes Acoustic Emission by stress waves. These stress waves can be measured by special AE-Sensors, which work like microphones. These Piezo-electric sensors listen into the structure and if a stress waves caused by a damage move through the part the sensor is able to measure the sound waves. To localise the defect or the damage a network of these sensors can be used. Installed in a network with known coordinates it is possible to determine the distance between the damage and the sensors around it by triangulation.

Large areas of Structure can be monitored with a network of AE Sensors. Usually a network is installed at areas where Acoustic Emissions are expected. However, this exposes the system to the risk of not detecting all damage. The AE data is recorded during flight. A conventional analysis approach is done on the ground but a Data Acquisition during flight is also possible.

AE can be applied on metal and composites structures. However, a calibration procedure is necessary.

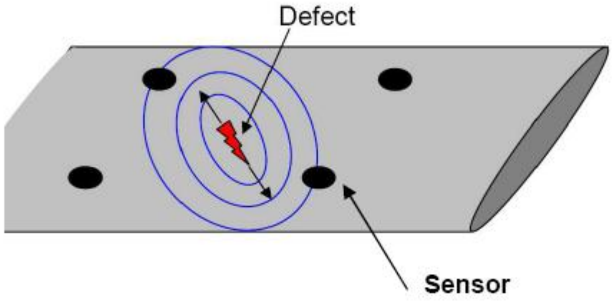

Figure 2.5-1 Acoustic Emission Principle

Acousto Ultrasonic (Pitch-Catch)

Acousto Ultrasonic (AU) uses the same principles as AE but with one fundamental difference: instead of just listening into the structure each transducer can act as an actuator whilst another is acting as a sensor.

The actuator sends a signal into the structure and the sensor receives the signal. The communication on undamaged structure between actuators and sensors is known and recorded. The distance between the two sensors is known too and the time the signal needs to propagate through the material can be measured. Every change in communication can be measured and damage can therefore be detect. AU can be organised in a network which is capable of monitoring large structures. The application and analysis is similar to AE. An important benefit is that in-Service no Calibration is strictly necessary. Finally, AE can be applied on metal and composites structures.

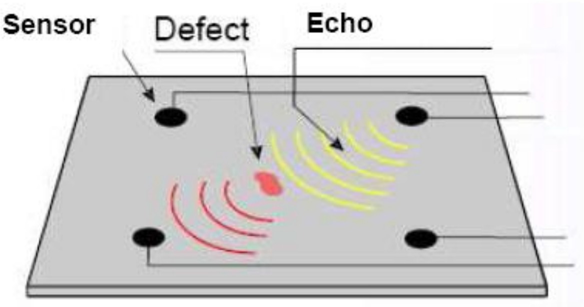

Figure 2.5-2 Acousto Ustrsonic (Pitch-Catch) Principle

Phased Array Ultrasonic (Pulse-Echo)

A Phased Array system for SHM uses the Pitch-Catch idea in another configuration. Sensors and actuators are placed in an array. In this configuration it is possible to use the array to send a guided signal through the structure. In an array every transducer is acting as both actuator and sensor to scan the part and detect the damage. With the known velocity of sound the waves are propagating through the material and the measured time for the detection it is also possible to localise the defect.

The application of Pulse Echo is local and a Sensor Array is usually working autonomously. Applications on metallic structures seem to provide consistent results, whilst application on composites have not reached the same maturity level.

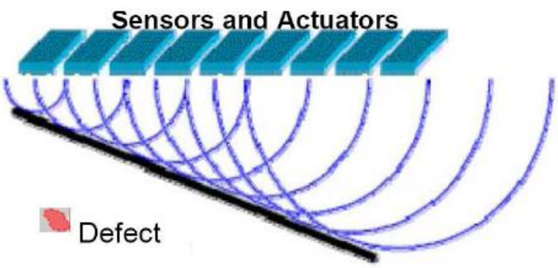

Figure 2.5-3 Phased Array Ultrasonic (Pulse-Echo) Principle

Fibre Bragg Gratings

Fibre Bragg Gratings (FBG) use UV-Laser light sent through an optic fibre to measure strain. Based on this information damage or delaminations can be inferred. The optic fibre is embedded or bonded to a

structure and if the structure is subject to a deformation the fibre elongate. Under this circumstances, the laser is refracted and differences in the measured index of refraction indicate the presence of a deformation. Depending on the application the fibre is embedded in different forms as coils or spirals to cover potentially large structures. One problem with FBG is the surface application bonding or the low maturity of embedding techniques.

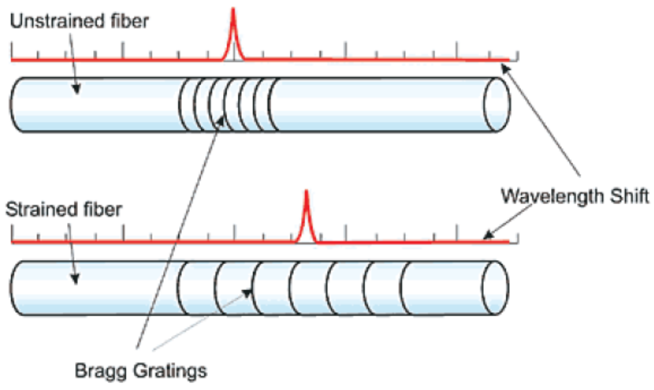

Figure 2.5-4 Fibre Bragg Gratings Principle

Comparative Vacuum Monitoring

Comparative Vacuum Monitoring (CVM) is a complete different approach. CVM is a measure of the differential pressure between fine galleries containing a low vacuum alternating with galleries at atmosphere in a simple manifold. If no flaw is present, the vacuum will remain at a stable level. If a flaw develops, air will flow through the passage created from the atmosphere to the vacuum galleries. Sensors may either take the form of selfadhesive polymer "pads" or may form part of the component. A transducer measures the fluid flow between the galleries.

The CVM Sensors work very locally and to monitor a large structure many sensors and equipment are required. Another problem is that a crack can only be detected if it connects to pressure galleries. Cracks which, for example, just move along on gallery or are under the surface can not be detected. CVM can be applied on both metal and composites structures.

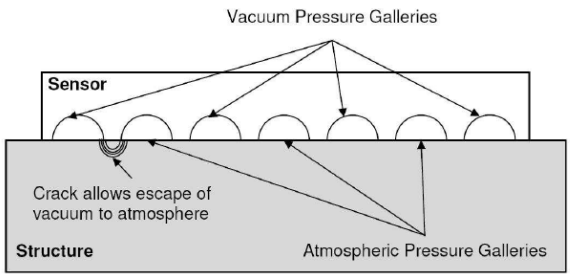

Figure 2.5-5 Comparative Vacuum Monitoring Principle

3.0 MONITORING OF REPAIRS

Figure 3.0-1 shows the types of maintenance downtime which occur during peacetime operations as well as during wartime deployments. During peacetime operations, the emphasis is on scheduled operations, and overall flight safety objectives dominate the (often very conservative) strategy adopted for scheduled maintenance operations. Unscheduled maintenance during peacetime operations is normally accomplished immediately after a failure occurs, regardless of the seriousness of the failure. In peacetime, the main aim of repair is the recovery of an aircraft to a standard that recovers its design capability over its remaining service life. This is achieved by the restoration of the structure to meet the requirements of the original design standard. Additionally, the aircraft systems are normally restored to full functionality regardless of their importance.

On the other hand, combat maintenance aims at keeping the aircraft in a basic operational condition. This often occurs in operational situations where recovery times may be severely limited, service life, and consequently durability considerations, assume a lesser degree of importance, and the functionality of certain systems and/or their associated components is not always essential when the more immediate requirements of a particular operational mission are considered.

In this context, Structural Health Monitoring (SHM) can play a fundamental role in the monitoring and assessment of the damage as well as in monitoring the quality of a repair. The following sections will concentrate on this latter aspect in which SHM techniques are utilised to monitor the integrity of a repair.

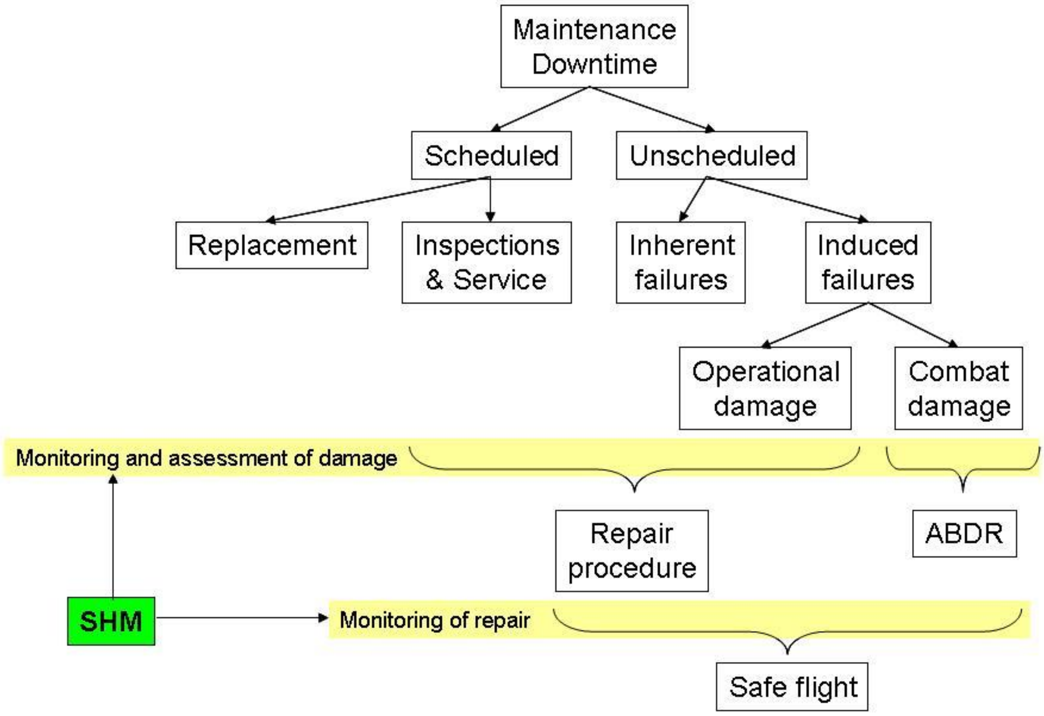

Figure 3.0-1: Types of Maintenance Downtime

3.1 SHM for ABDR

The Aircraft Battle Damage Recovery (ABDR) covers the rapid identification, assessment and recovery of battle-type damage to an aircraft, aimed at restoring a level of flight and mission capability as required to

fulfil immediate operational requirements at a time of conflict. The ABDR information is intended for use by personnel working in an operational environment, generally with limited facilities and support equipment. Information relating to battle damage and its effect on the aircraft or monitoring of the integrity of repairs can be obtained with appropriate SHM techniques in order to decide if some form of recovery action is necessary (NO-GO) or if the aircraft can be employed as is (GO). Therefore the aim of the SHM system is to identify an absolute minimum standard of aircraft structural integrity, which if not available, precludes any flight by the aircraft.

3.2 General requirements for Monitoring of Repairs

Because of the different operational nature between peacetime and wartime deployments, the requirements for SHM of Repairs assume different connotations, as described below.

3.2.1 Peacetime requirements for Monitoring of Repairs

In monitoring a repair, in order to justify the use of SHM techniques, an SHM system shall be able to provide a more comprehensive and timely set of information than other classical NDI techniques. This shall be done in order to assess the integrity not only of the repair, but also of the structural component containing the repair. In other words, with reference to Figure 2.1-1, similar SHM techniques should be applicable to both the monitoring and assessment of a damage as well as the monitoring of a repair. Therefore, an SHM system shall:

- pose no health and safety hazards to personnel engaged in maintenance activities
- identify damaged structures
- assess the degree of damage in order to determine which damaged items must be repaired or replaced, which may be left in a damaged state and which can be isolated
- monitor damage growth of repaired items
- support the correlation with other aircraft data in order to estimate the degree of degradation remaining and assess its effect on the operational capability of the aircraft

In particular to SHM of Repairs, an SHM system shall be able to monitor any type of metallic and non-metallic combinations of structures being repaired and the repair material themselves.

3.2.2 Wartime requirements for Monitoring of Repairs

In wartime operations, time is critical and the complexity of the on-ground equipment shall be kept to a minimum. To quickly determine if the integrity of a battle damaged repair can keep the aircraft in its operational readiness, the wartime SHM technique shall be able to gather essential information in a very short period of time using relatively simple equipment. Such essential information shall comprise information on:

- the degradation of the repair
- location and type of the monitored repair

This basic information is then correlated with aircraft-specific information contained in the ABDR (Section 3.3) such as permissible structural damage limits and overall system degradation information in order to determine if action is needed on the monitored repair (NO-GO) or if the aircraft can be operated as is (GO).

Comparing the above general peacetime and the wartime requirements, a fundamental question that can be posed is whether the same SHM system could fulfil both sets of requirements. Although the SHM

community has not found a conclusive agreement on this topic, the general trend indicates that because of the very different nature of repairs which are carried out during peacetime and wartime operations, an "SHM solution that fits all" is unlikely to be found. As an example, Figure 3.2-1 shows a wet wing integral tank being hit by a bullet which generates secondary damage effects. This type of damage can only occur in wartime and because the structural integrity margins are still acceptable for wartime operations an essential repair effort of such wing tank is possible before giving the aircraft a "GO" status. The nature of damage occurring during peacetime operations can be significantly different, therefore repair techniques are likely to be very different implying that any SHM monitoring done on a repaired structure as shown in Figure 3.2-1 would not be acceptable in peacetime operations.

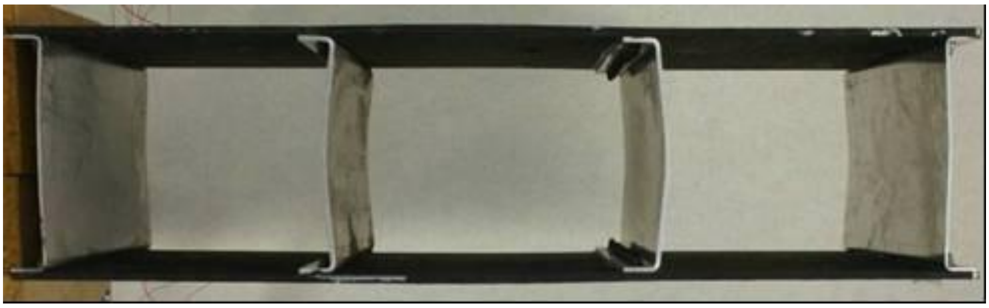

Figure 3.2-1. Damaged Wing Integral Tank

4. REMAINING OBSTACLES OF SHM FOR REPAIRS

In general and specifically for repairs the main shortcomings of existing SHM systems and the obstacles concerning an introduction on the market can be summarised as follows:

4.1 Lack of technical maturity

- Most of the proposed solutions only solve specific problems of a SHM system. The respective focus regards sensor technology, data analysis, signal-damage correlation etc. Operators still miss an integrated large scale demonstrator.
- It is difficult to match all the environmental parameters such as temperatures, loads, electro-magnetic compatibility, chemical contaminants, which occur at operational conditions.
- A complete health monitoring system for one aircraft is difficult to implement given the available level of technology.
    - Part of the challenge is to determine suitable locations and level of needed information.
    - Another challenge is the correlation of existing low level monitoring systems in order to perform a general health assessment of the aircraft.

4.2 Lack of acceptance by operators

- Complicated and long-term certification process expected.
- Inertia of current manual inspection interval procedures.
- Scepticism against new technologies with minimal service data.
- Cost implications for new hardware, software and training.
- Pessimistic expectations concerning the return-of-investment.

Although a number of applications are currently operational in a number of special cases, the airworthiness of such systems requires a really long-term reliability of the SHM systems under harsh operational conditions. It is therefore required to have a system where all kind of tests were performed which are typical for in-service tests of usual aircraft components. [7]

4. 3 Remaining Obstacles of SHM for ABDR

For ABDR the main shortcomings of existing SHM systems and the obstacles concerning for application be summarised as follows:

- Application of a SHM System in a battlefield scenario is too complex in view of system complexity, labour effort, installation time.
- Battle damage scenarios are very unpredictable and therefore monitoring such type of damage would require an extensive testing effort for defining a comprehensive system lay-out.

5.0 BENEFITS OF SHM OF REPAIRS

Knowing the integrity of in-service structures on a continuous real-time basis is a very important objective for manufacturers, end-users and maintenance teams. In effect, SHM:

- allows an optimal use of the structure, a minimized downtime, and the avoidance of catastrophic failures, (Figure 5.0-1)
- gives the constructor an improvement in his products, for example offering the capability of estimating the remaining useful life of a repaired component
- drastically changes the work organization of maintenance services:
  - by aiming to replace scheduled and periodic maintenance inspection with performance-based (or condition-based) maintenance (long term) or at least (short term) by reducing the present maintenance labour, in particular by avoiding dismounting parts where there is no hidden defect;
  - by drastically minimizing the human involvement, and consequently reducing labour, downtime and human errors, and thus improving safety and reliability.

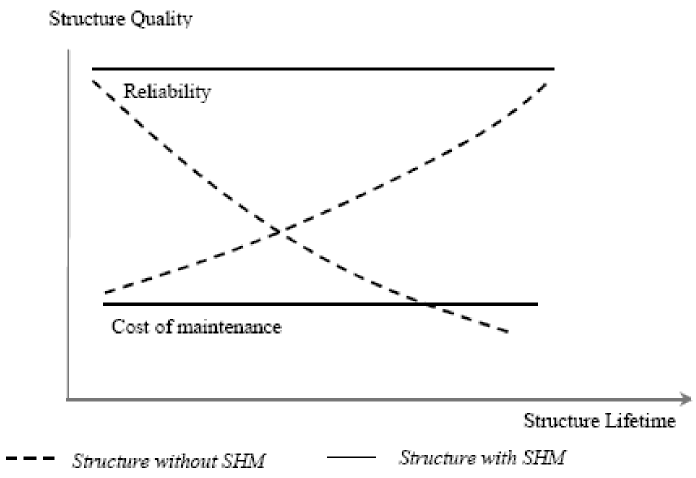

Figure 5.0-1: Benefit of SHM for end-user [8]

6.0 CONCLUSIONS

Most current structural and mechanical system maintenance is done in a time-based mode (scheduled maintenance). SHM is the technology that will allow the current scheduled maintenance philosophies to evolve into potentially more cost effective condition-based maintenance philosophies. The concept of condition-based maintenance is that a sensing system on the structure will monitor the system response and notify the operator that damage has been detected. Life-safety and economic benefits associated with such a philosophy will only be realized if the monitoring system provides sufficient warning such that corrective action can be taken before the damage evolves to a failure level. The trade-off associated with implementing such a philosophy is that it requires a more sophisticated monitoring hardware to be deployed on the system and it requires a sophisticated data analysis procedure that can be used to interrogate the measured data.

In order to satisfy future requirements of mission availability the maintenance effort must be reduced with a higher level of planning. Therefore concepts like Condition Based Maintenance are essential and they ask for SHM.

In particular for monitoring of repairs the development of robust SHM technologies has many elements that make it a potential ‘grand challenge’. This is particularly true for SHM of ABDR.

However, performing such type of monitoring presents tremendous economic and life-safety benefits that justify their continuous improvements.

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